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Design by taking perspectives: How engineers explore problems

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Abstract
Background: Problem exploration includes identifying, framing, and defining design problems and bounding problem spaces. Intentional and unintentional changes in problem understanding naturally occur as designers explore design problems to create solutions. Through problem exploration, new perspectives on the problem can emerge along with new and diverse ideas for solutions. By considering multiple problem perspectives varying in scope and focus, designers position themselves to increase their understandings of the "real" problem and engage in more diverse idea generation processes leading to an increasing variety of potential solutions.

Purpose/Hypothesis: The purpose of this study was to investigate systematic patterns in problem exploration in the early design phases of mechanical engineers.

Design/Method: Thirty-five senior undergraduate students and experienced designers with mechanical engineering backgrounds worked individually following a think-aloud protocol. They explored problems and generated solutions for two of four randomly assigned design problems. After generating solutions, participants framed and rewrote problem statements to reflect their perspectives on the design problem their solutions addressed. Thematic analysis and a priori codes guided the identification of problem exploration patterns within and across problems.

Results: The set of patterns in engineers' problem exploration that emerged from the analysis documents alternative strategies in exploring problems to arrive at solutions. The results provide evidence that engineering designers, working individually, apply both problem-specific and more general strategies to explore design problems.

Conclusions: Our study identified common patterns in the explorations of presented problems by individual engineering designers. The observed patterns, described as Problem Exploration Perspectives, capture alternative approaches to discovering problems and taking multiple problem perspectives during design. Learning about Problem Exploration Perspectives may be helpful in creating alternative perspectives on a design problem, potentially leading to more varied and innovative solutions. This paper concludes with an extended example illustrating the process of applying Problem Exploration Perspectives to move between problem perspectives to generate varied design outcomes.

Keywords
creativity, design, idea generation, problem definition, problem exploration

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Design by taking perspectives: How engineers explore problems

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1 | INTRODUCTION

Design, a core competency in engineering, is defined as an iterative process drawing on content knowledge, engineering skills, and reasoned judgment. In professional practice, engineers are often presented with design problems from management, clients, and product users, and must then identify the problem to address when searching for solutions (ABET Board of Directors, 2016; McDonnell, 2015; Rittel, 1988). However, in engineering education, a "design brief" is typically presented for students to adopt in creating potential solutions. Many studies investigate how engineers develop solutions (e. g., Atman et al., 2007; Daly, Yilmaz, Christian, Seifert, & Gonzalez, 2012; McGuire, 1973); however, less is known about how designers change the presented problem during the solution process (Cross & Clayburn Cross, 1998; Dorst & Cross, 2001). Problem exploration—recognizing, framing, and defining a need—has been identified as a critical component of design processes (Goel & Pirolli, 1992; Paton & Dorst, 2011; Volkema, 1983).

Design problems are inherently ill-structured and open-ended (Cross, 1984; Dorst, 2006; Farrell & Hooker, 2013; Simon, 1977), with vague initial states, unspecified goals, and indeterminate pathways between problems and solutions (Goel & Pirolli, 1992; Goldschmidt, 1997). Designers must transform these ill-structured components to define solvable problems (Nadler, Smith, & Frey, 1989) that capture the "real, " underlying issue[s] beneath the presented problem (Csikszentmihalyi & Getzels, 1971, 1988; Daly, McKilligan, Studer, Murray, & Seifert, 2018; Fogler & LeBlanc, 2014). Without exploration, designers run the risk of solving the "wrong problem" (Volkema, 1983, p. 648).

Alternative perspectives emerge as designers explore presented problems. For example, preventing the spread of germs in hospitals can be viewed as the need to avoid exposure (e. g., wearing gloves) or to recover from exposure (e. g., washing hands). An alternative perspective has the potential to shift designers' views about core elements of a problem and may redirect the designer toward different solutions (Hey, 2008; Hey, Linsey, Agogino, & Wood, 2008). While the importance of problem exploration in design has been identified (Crismond & Adams, 2012), empirical evidence of strategies is lacking (Studer, Daly, McKilligan, & Seifert, 2018). Identifying patterns in design problem exploration may uncover ways to facilitate it and lead to more innovative design outcomes.

To identify strategies engineers use in their exploration, we observed mechanical engineering students and practitioners as they generated multiple design solutions for two problem statements and refined an initial presented problem to one that they considered more aligned with their solutions. Across designers, we sought for generalized patterns identified in multiple design problems and solutions. These patterns may prove useful as explicit strategies for problem exploration to help other designers move from presented problems to more varied problem perspectives leading to more innovative solutions.

2 | BACKGROUND

2.1 | Defining problem exploration

Engineering problems are defined as well structured when they allow the application of known operators toward solutions (Cropley, 2015; Simon, 1973). Design problems are defined as ill-structured as potential paths to solutions are indeterminate (Goel & Pirolli, 1992; Jonassen, 1997; Newell & Simon, 1972); that is, design requires many iterative decisions to clarify purpose, contexts and features throughout a design process (Simon, 1973). These decisions begin with understanding the presented problem by working to identify the current and goal states, recognize constraints, and consider alternative perspectives in defining discovered problems. The identification and interpretation of the problem guides designers' processes and has a significant impact on outcomes (Crismond & Adams, 2012; Cross & Clayburn Cross, 1998; Dorst & Cross, 2001; Schön, 1984). Following Dewey (1910), we refer to these exploratory investigations of ill-structured design problems as Problem Exploration.

Problem Exploration entails investigating problems through perspective-taking to determine salient features and underlying needs to drive the search for creative solutions (Duncker & Lees, 1945). Exploring problems has been posited as the first stage of problem-solving models; for example, according to Wallas' (1926) four-stage process model, generating possible solutions should occur after thoroughly investigating problems. Separating an initial stage of problem understanding from the later search for solutions was essential to the development of Newell and Simon's (1972) computational approach. However, for creative solutions, Einstein and Infeld (1938) note, "the formulation of the problem is often more essential than its solution, which may be merely a matter of mathematical or experimental skill. To raise new questions, new possibilities, to regard old problems from a new angle requires creative imagination and marks real advances in science" (p. 92).

More recently, systematic reviews of problem exploration research in engineering design and education demonstrate a broad range of definitions (cf. Crismond & Adams, 2012; Cross, 2004). Synonymous with "scoping" or "setting" a problem,

problem exploration is defined as the process of formulating the problem space (Atman, Chimka, Bursic, & Nachtmann, 1999; Dillon, 1982; Nadler et al., 1989; Runco & Chand, 1994; Schön, 1983; Volkema, 1983). Problem framing is defined as a transformation of problem characteristics to align with imposed frames of reference (Dorst & Cross, 2001; Schön, 1984, 1988; Stumpf & McDonnell, 1999), establishing coherence through problem boundaries (Schön, 1988). Other definitions emphasize the roles of the designer's experience, values, interpretations, and methods of inquiry in determining problems and goals (Lloyd & Scott, 1994; Schön, 1984), such as a value-laden problem frame (Dorst & Cross, 2001; Paton & Dorst, 2011) or perceiving problems in specific situations, analogs, or solutions (Lloyd & Scott, 1994; Mumford, Reiter-Palmon, & Redmond, 1994). Merrifield, Guilford, Christensen, and Frick (1962) determined that definitions of problem exploration have included sensing, recognizing, or finding previously unidentified problems, and that these approaches lead to more creative solutions (Getzels, 1975, 1979). In addition, exploring as redefining alternative perspectives (Einstein & Infeld, 1938; Mumford et al., 1994; Mumford, Baughman, Threlfall, Supinski, & Costanza, 1996; Nadler et al., 1989; Volkema, 1983) can lead to different approaches arising from differing points of view (Wallas, 1926).

2.2 | Strategies for problem exploration

Some proposed strategies (see Table 1) for problem exploration already exist to guide designers. MacCrimmon and Taylor (1976) described problem formulation in industrial engineering and management domains and introduced a set of four decision strategies. Fogler and LeBlanc (2014) outlined problem exploration methods for student engineers. Two other approaches include the "5 Whys" (Bulsuk, 2009; Morgan & Liker, 2006) and Spradlin's (2012) process for defining problems by establishing and justifying the need, and then contextualizing and writing a problem statement.

Only one study by Volkema (1983) provided empirical evidence that the proposed exploration strategies were effective, leading to more solutions. Engineering and counseling students were instructed to either focus on defining the problem by themselves or were trained with guided instruction on the Problem-Purpose Expansion technique. Engineers solving counseling problems and counselors solving engineering problems generated more solutions than when engineers and counselors designed solutions within their fields. This method reframes problem statements to expand the solution space, for example, removing a constraint (e. g., patient stays in hospital) to broaden solution possibilities (Stanhope & Lancaster, 2015) (e.g., to include home visits, informal care, or skilled home care). Intentional use of strategies during problem exploration has the potential to improve design outcomes.

2.3 | Linking problem exploration to creative design

Empirical evidence links problem exploration to creative outcomes in artists asked to design and execute a still life drawing (Getzels & Csikszentmihalyi, 1977). Those observed to find their problems by deliberately creating and altering the composition had more creative outcomes as judged by independent experts (Csikszentmihalyi & Getzels, 1971); and 18 years later, these same artists exhibited higher levels of professional success as measured by recognition and income (Csikszentmihalyi & Getzels, 1988). This longitudinal study tying problem exploration behaviors within a single test session to real-world creative outcomes 10 years later suggests that problem exploration may play an important role in creative design.

Empirical studies of everyday problem solving have also supported this link, showing that children's problem exploration skills are the best predictor of later creative success (Okuda, Runco, & Berger, 1991). Consistent with these findings, a study of industrial designers working independently found they imposed frames of reference to shape the problem, and those who focused more on understanding the problem in greater depth generated more creative outcomes (Christiaans, 1992). Designers presented with the same problem may generate unique solutions when they interpret and approach problems through diverse frames or perspectives (MacCrimmon & Taylor, 1976).

Other studies revealed that experts focused more on defining and framing problems than those with less experience, both in engineering domains (Atman et al., 2007; Cross & Clayburn Cross, 1998) and in art and science (Rostan, 1994). In a protocol study of playground design (Atman et al., 2007), expert engineers gathered more information on potential problems than students and spent more time understanding and iterating on the overall task. In their study of two engineering design experts, Cross and Clayburn Cross (1998) found both chose to frame their view of the problem in a challenging way. Despite different design tasks, both experts engaged in framing problems systemically by identifying primary issues and constructing a frame to focus and bound the problem (Schön, 1983). Experts appear to flexibly move in and out of varied problem definitions in search of novel perspectives, underlying needs, and opportunities for innovation (Cross, 2011).

Problem exploration may also help to reduce the likelihood of design fixation, a problem documented in studies with mechanical engineers and other designers (Dorst & Cross, 2001; Jansson & Smith, 1991; Pahl & Beitz, 1996; Paton & Dorst, 2011; Sio, Kotovsky, & Cagan, 2015). Focusing on existing examples can impede the generation of more novel designs due

TABLE 1 Proposed strategies for problem exploration

MacCrimmon and Taylor (1976)
Forming boundaries, or questioning assumptions
Examining changes, or focusing on any alterations in the problem description
Subdividing problems using methods such as morphological analysis (Hall, 1962) and attribute listing (Rickards, 1975)
Addressing malleable components, or selective focusing (Shull, Delbecq, & Cummings, 1970)
Volkema (1983)
Problem Formulation Heuristics
Problem reduction
Problem expansion
Problem-purpose expansion technique
The purpose is to consider how goals at different levels are related to one another.
1. Initially formulate a frame based on a predefined format.
2. Reformulate the statement again by asking "What are we trying to accomplish?"
3. Ask the same question again.
Bulsuk (2009)
"5 Whys" method
Repeatedly asks "Why?" until a cause and effect relationship emerges
Fogler and LeBlanc (2014)
Critical thinking questions probe assumptions and shift perspectives
Present state/desired state analysis coupled with Duncker diagrams (where you are now and where you want to go)
Parnes' (1967) statement-restatement method to suggest triggers that expand problem statements
Kepner and Tregoe (1981) problem analysis technique with four strategies (identify, locate, timing, and magnitude) and probing questions.
Spradlin (2012)
Problem-definition process
Establishing the need
Justifying the need
Contextualizing the problem
Creating a discovered problem statement to frame the presented problem

to multiple influences, such as existing designs, unconscious or intentional resistance to new ideas (Youmans & Arciszewski, 2014), and overcommitment to initial designs (Viswanathan & Linsey, 2012). However, by engaging in problem exploration and intentionally changing perspectives on a presented problem, creating alternative solutions may become more likely (Dorst, 2010).

Most importantly, a perspective imposed on problems through exploration strategies can guide solution approaches (Holyoak, 1984; Lloyd & Scott, 1994; Newell & Simon, 1972; Schön, 1983). For example, problem constraints intentionally altered based on contextual knowledge or perceptions of problem elements may direct attention to solutions including these features. Imposing a new frame or problem representation can guide exploration (Holyoak, 1984; Newell & Simon, 1972). While Dewey (1910) defined problem exploration as preceding solution generation, more recent research has observed oscillation between problem exploration and idea generation phases, termed the co-evolution of problem and solution (Cross, 1997; Dorst & Cross, 2001; Maher, Poon, & Boulanger, 1996a, 1996b). In one study, nine designers were asked to create a waste removal system on a train and independently chose to restructure the presented problem to include a newspaper reuse system (Dorst & Cross, 2001). The interplay between problem exploration and solution generation may heighten the importance of using intentional strategies to explore problems.

A recent study of online design challenges examined the relationship between changes to presented problems and the success of design outcomes (Studer et al., 2018). Designers with varied backgrounds submitted designs in response to presented problems in online design challenges. The challenges required that each submitted solution include a paired problem redefinition written by the designer, and more than 200 problem–solution pairs were examined. Analysis revealed that more changes from presented to redefined problems were associated with better solution outcomes as evaluated by challenge judges. This study identified 42 distinct patterns of problem exploration in the problem–solution pairs. While these patterns of problem exploration suggest specific strategies for exploring design problems, there is no evidence that the designers made use of these strategies as they actively worked on design problems. Examining problem exploration during active design is required to document strategies for uncovering alternative problem perspectives.

3 | RESEARCH OBJECTIVES

The goal of this study was to examine patterns of problem exploration as exhibited by individual engineers working independently as they explored design problems and generated solutions. We consider problem exploration as the deliberate and acuminous search for diverse perspectives, which in turn influence problem interpretation and the generation of solutions. We focused on determining the cognitive strategies engineers used to explore design problems on their own without intervention. We asked mechanical engineering practitioners and students to solve open-ended design problems, and recorded their cognitive processes through a think-aloud method (Gero & Tang, 2001; Hay et al., 2017). These research questions guided the study:

1. What patterns of problem exploration emerge as mechanical engineers develop solutions to design problems?
2. To what extent do mechanical engineers employ similar patterns of problem exploration across different design problem contexts?

4 | METHOD

We adopted Getzels' (1975) terminology describing a presented problem as provided or given to designers and a discovered problem as the resulting problem description developed by a designer as a result of problem exploration.

4.1 | Participants

We collected data from graduate and senior undergraduate students in mechanical engineering programs at two large Midwest research institutions, invited through email list-servs. Engineering practitioners were invited through individual researcher contacts. Thirty-five participants volunteered for the study, with 15 seniors and 15 graduate (MS and PhD) students reporting varied design experience in both formal and informal contexts in both academia and industry settings (see Table 2). The five practitioners had at least 1 year of engineering design experience in industry settings, and four were simultaneously enrolled in graduate engineering programs. Students were compensated $30 and practitioners $50 for their participation.

We chose mechanical engineering design as an exemplar of the design tasks evident in the field of engineering. Purposively selecting (Teddlie & Yu, 2007) participants in mechanical engineering also aligned with much of the study of engineering design in the literature, with primary sampling done in mechanical engineering, and allowed us to control for discipline to investigate the extent of diverse approaches within a single discipline. Further, this assured that the design tasks were reasonably aligned with tasks common to participants' disciplines.

4.2 | Data collection

The individual design sessions employed a concurrent protocol method (also known as a think-aloud or verbal protocol) (Ericsson & Simon, 1993; Fonteyn, Kuipers, & Grobe, 1993; Lloyd, Lawson, & Scott, 1995) where participants spoke their thoughts as they developed solutions to a presented design problem. Cognitive protocol analysis is an informative approach for analyzing designers' cognitive processes (Dorst, Christiaans, & Cross, 1996; Purcell & Gero, 1998; Stauffer & Ullman, 1991) used to study designers' thinking processes (Dinar et al., 2015; Dorst et al., 1996; Stauffer & Ullman, 1991). The method allows for the examination of the design process in action (Akin, 1993) with minimal disruption of cognitive performance (Ericsson & Simon, 1993). As designers verbalize their thoughts as they occur, they may reveal what participants understand, what they pay attention to, and what guides them (Bernadowski, 2016; Bilda, Gero, & Purcell, 2006; Gotwals & Songer, 2013; Pergams, Jake-Matthews, & Mohanty, 2018; Stieff, 2011; Wiltschnig, Christensen, & Ball, 2013). This think-aloud method provides researchers with data not otherwise accessible about thoughts contributing to the creation of final explanations or solutions.

TABLE 2 Educational attainment and gender of participants

Educational program	Male	Female
Undergraduate seniors	9	6
Master's students	7	1
PhD students	5	2
Practicing engineers	4	1

Each engineer also participated in a short retrospective interview targeting their perceptions about how they changed the design problem. This combination of concurrent with retrospective data has been used successfully in other studies of design cognition (Daly et al., 2012; Purcell & Gero, 1998; Suwa, Purcell, & Gero, 1998).

4.2.1 | Procedure

Participants first completed a short survey asking about their gender, engineering experience, and level of comfort with exploring, formulating, and analyzing problems. The think-aloud protocol method with voice recording was then introduced to the participants, and they were informed that the researcher would prompt them if they paused to remind them to continue speaking their thoughts aloud.

Then, they were asked to generate solutions to a presented design problem. Written instructions provided information about the task:

> *Read the given problem statement below and ensure your understanding of the task. Feel free to use this sheet of paper for any annotations or notes. On the provided sheets of paper, sketch and describe as many solutions to the problem as you can think of in the time allotted [25 minutes]. If you finish before the time is up or you've exhausted the number of solutions you can think of, please notify the researcher to move on to the next task.*
> *Please **think aloud** as you complete this task.*

Participants generated solutions for their first presented problem for 25 min, drawing concept sketches and making notations to document each idea while simultaneously thinking aloud. Participants completed a concept sheet to record each idea.

Next, participants had 15 min to write a discovered problem statement aligning with each of their identified solutions. The instructions for writing discovered problem statements read as follows:

> *For each of the solutions you generated, write a problem statement that would allow other [student engineers/ designers] to come up with the same solution you developed. Imagine that what you write is the only thing they would see (the given problem statement would not be available). Consider the background, the need, and the constraints and criteria.*
> *Please **think aloud** as you complete this task.*

While this task was likely new to the participants, all indicated they understood the question.

Following this task, participants completed 5-minute retrospective interviews discussing (a) how the discovered problem statements resembled and differed from the presented problem; (b) the focus of each discovered problem statement; (c) why they selected the criteria, constraints, stakeholders, and scenarios they did; and (d) why they decided to exclude particular components of the presented problem.

This sequence of activities was then repeated with a second design problem. We employed four presented problems for this research counterbalanced in combinations and serial order and assigned at random to participants. The duration of the entire session was 90 min.

4.2.2 | Materials

The four design problems were inspired by the Grand Challenges for Engineering (National Academy of Engineering, n. d.) and design problems in studies of design processes (Adams, Turns, & Atman, 2003; Atman et al., 1999; Atman & Bursic, 1998; Atman, Kilgore, & McKenna, 2008; Atman & Turns, 2001; Daly et al., 2012) and represented significant topics with varied context and complexity. The selection of conceptual problems minimized the need for specialized knowledge and allowed a focus on the generation of alternative solutions. Because each problem was novel to the participants, solution bias from standard or obvious solutions was minimized:

> **Disaster Relief** *In areas recently stricken by natural disasters (tsunamis, earthquakes, hurricanes, floods, tornados, etc.), large populations are suddenly made homeless and lose access to electricity. Disaster relief efforts focus on rescue, and supplying food and shelter to victims, often meaning that electrical power can be inaccessible for a very long time. Your task is to design a deployable device(s) that can be used at the site of a disaster relief effort. They should be suitable for quick deployment and set-up and should be operable by everyday citizens, including victims of the disaster.*
> **Clean Water** *The National Academy of Engineering has identified access to clean water as one of the most significant challenges. For this task, you are to design a device to help provide clean water to those without an adequate supply. Consider varied aspects and function[s] of the device.*
> **Playground** *A city resident has recently donated a corner lot for a playground. You are an engineer who lives in the neighborhood, and you have been asked by the city to help with the project. Your task is to design playground equipment for the lot using locally sourced materials that are able to withstand outdoor conditions all year long.*
> **Solar Oven** *Sunlight can be a practical source of alternative energy for everyday jobs, such as cooking. Simple reflection and absorption of sunlight can generate adequate heat for this purpose. Your task is to develop a product or a system that utilizes sunlight for heating and cooking food. The product or system should be practical for everyday adults to use.*

4.3 | Data analysis

We examined each participant's data as a whole by problem to identify patterns of problem exploration. Each data set included all of their think-aloud session transcripts, concept sketches and written notations, written versions of their discovered problem statements, and their retrospective interview transcript. Connections between these data sources were considered in identifying intended meaning within a problem. The qualitative analysis method was similar to prior studies extracting cognitive strategies evident in design behaviors using verbal protocols (Daly et al., 2012; Dorst et al., 1996; Yilmaz & Seifert, 2011; Yilmaz, Seifert, & Gonzalez, 2010). We started with an initial list of codes from a previous study of online design challenges (Studer et al., 2018) (see Appendix), where each code represented a problem exploration pattern.

The two coders had both engineering and graduate degrees; one had previous experience coding patterns of problem exploration in a prior study, while the other had extensive experience with qualitative research analysis and a graduate certificate in qualitative research. Both first independently coded the same set of data for one problem (Disaster Relief). The coders began by reading through the Disaster Relief problem data to gain a holistic sense of the data through thematic analysis (Braun & Clarke, 2006). The first round of analysis commenced with structural and concept coding (Saldaña, 2015) of the data, proposing new emergent codes representing previously unidentified patterns as needed. For example, the code, "detail the operational requirements," represents a problem exploration pattern emerging from this data set not identified in prior data. These emergent codes were added to the codebook, and the two coders discussed all coding differences to consensus.

Next, the two coders independently analyzed the Clean Water design problem data with the new and pre-existing codes. Inter-rater reliability averaged 87%. Table 3 shows the Cohen's Kappa values computed using SPSS for each problem exploration pattern. The values indicated good agreement for each of the patterns coded from the prior study and the four new codes identified in the Disaster Relief data. Each coder then worked separately to complete the analysis of the other problem data sets.

4.3.1 | Uncovering exploration patterns

Figure 1 illustrates a portion (condensed for presentation) of the data set from one participant exploring the playground problem. The set includes one discovered problem statement, a description and a drawing of its paired solution, and the think-aloud and retrospective transcript. The bolded text within the discovered problem statement is consistent with segments appearing in the presented problem statement. The italicized words represent text segments researchers identified as evidence of patterns of problem exploration. Participant 30, a senior mechanical engineering student, designed a swing set concept focused on materials and user needs and desires. Her description emphasized *safety* and *comfort* (she noted that the swing

TABLE 3 Cohen's kappa for the clean water patterns of problem exploration

Problem Exploration Perspective	k
Add potential limitations	0.899
Break down the primary need (NEW)	1.000
Describe an existing solution to use as conceptual inspiration	1.000
Describe environmental conditions	1.000
Describe material characteristics	1.000
Describe secondary functions	1.000
Describe the desired appearance attributes	1.000
Describe the desired dimensions	1.000
Describe the setting	0.918
Describe the users' need	0.907
Detail the operational requirements (NEW)	0.902
Detail the required functions	0.786
Determine the primary user	0.899
Determine the required cost	1.000
Elaborate on a method/means (NEW)	0.973
Expand the primary stakeholder group	0.661
Focus on eco-friendly solutions	0.737
Focus on one setting/scenario (NEW)	0.737
Incorporate more scenarios	1.000
Integrate mobility	1.000
Modify existing solutions	0.661
Prioritize use cases	1.000
State the primary need	0.963
Utilize existing solutions	0.916

would need to be padded to make it soft and safe for babies or young children), and she stated there was a need for "a baby swing that is soft." She echoed this in the discovered problem statement, "Consider *safety* in your design." This participant provided evidence of the pattern, "determine the user's need" through her focus on handholds and their placement, and on ways to have fun on a standing and double swing. In addition, she explicitly described using metal, plastic, and rubber as primary materials, coded with the pattern, "describe material characteristics."

4.3.2 | Comparing patterns across problems

After coding all participants' data sets by problem, we examined the use of patterns by individual engineers across their two problems. Figure 2 illustrates the analysis of the data set provided by a male practitioner with 25 years of design experience in the automobile industry. This example shows three discovered problem statements for both the Solar Oven and Clean Water design problems. Figure 2 displays a Venn diagram of identified exploration patterns including both *unique* (problem-specific) and *common* (across problems) for the set of problem exploration patterns identified.

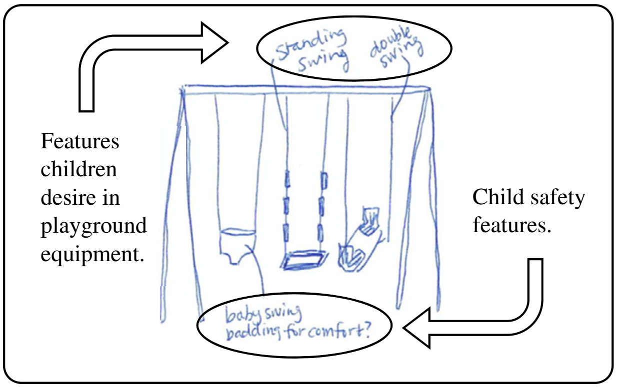
Participant 46 provides an example of using unique and common patterns across the two problems. With the Solar Oven design problem, he said one would need to travel to the American Southwest ("focus on the setting/scenario") for a solar oven to function correctly as temperatures there could climb as high as 100°, evidence for the strategy, "detail operational requirements." He also stated in the transcript:

> *The precondition would be . . . it's going to be only in the American southwest because there aren't enough days of sunlight to cook in the wintertime here. . . might not be even in the summertime. However, in the American Southwest [. . .].*

Playground Discovered Problem Statement

Design an innovative and fun piece of playground equipment using **locally sourced materials** that are able to **withstand outdoor conditions** all year long. Consider *safety* in your design.

Solution



Description

Swing set including a *baby swing that is soft*, standing swing, and double swing for two people. Made of *metal, plastic, rubber*, (standard swing materials).

Think-Aloud Transcript Excerpt

The baby swings are pretty standard. So, they've got this kind of pouch at the bottom where the kid sits. And I'm thinking about redesigning that but it seems like a pretty good solution already. You could *make it more comfortable for a kid* by *putting some sort of padding* inside but it would need to be *waterproof*, so that might be a little difficult. But it could be a possibility depending on what solutions are out there.

So, I'll just write that on here. . . .
And then maybe some *hand holds* on the side where it's *easier to hold on* to it.
So, *handles at various heights* because *people are different heights*.

FIGURE 1 One participant's data set demonstrating how data were coded [Color figure can be viewed at wileyonlinelibrary.com]

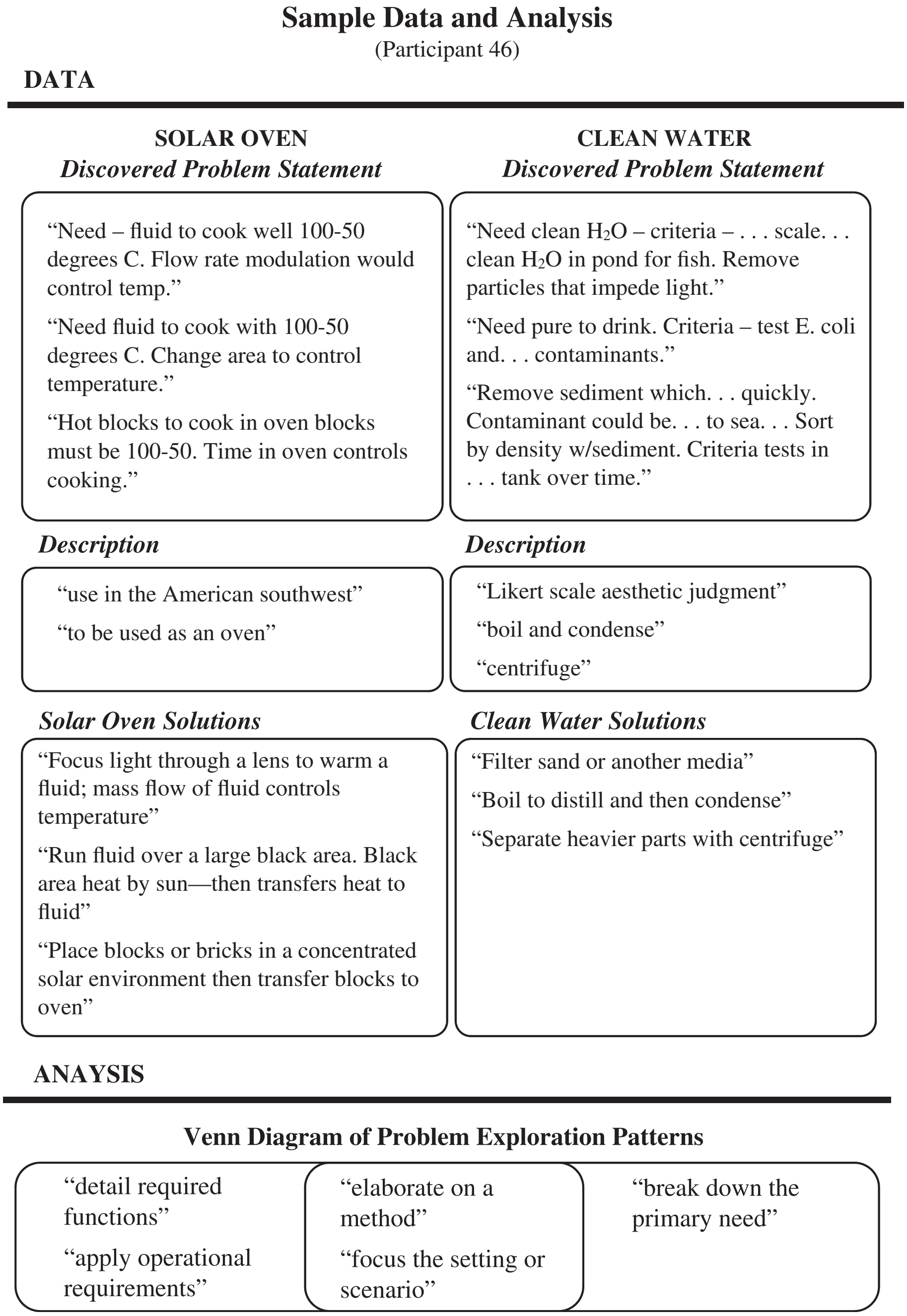
Participant 46 argued that extended daylight hours and consistently high temperatures were requirements for a solar oven to operate. His three discovered problems focused on adjusting the flow rate, changing the size of the surface area, and heating blocks as "functional requirements" needed to cook food at differing temperatures. All of his discovered problems "elaborated on a method" to heat an oven through solutions utilizing lenses, black surfaces, and heated blocks. From his transcript:

> *Here are three ideas. We're going to focus light through a lens, warm a fluid, and the mass flow rate of fluid will control the temperature. Or we're going to run a fluid over a large black area and let the black area absorb the sunlight and then transfer it to a fluid or we're going to use blocks in an area that's got concentrated sunlight in black blocks and you can transfer the blocks to the oven.*

Then in his second problem, he again "focused on the setting/scenario" (cleaning a fishbowl) for the first Clean Water discovered problem. Data from the second and third discovered problems did not specify a scenario, but instead emphasized two methods of heating water to meet differing levels of cleanliness. Discovered Problem Two focused on the removal of biotic debris, and the third indicated the primary need to remove sediment. The latter two discovered problems detailed procedures ("elaborate on a method/means") for cleaning and testing water to meet their imposed requirements. Each of his discovered problems was coded for the patterns "break down the primary need" and "elaborate on a method/means." In the following excerpt, he emphasized the need to clean and test water (again, "break down the primary need") to validate cleanliness. Also, he elaborated on three different (filter, boil, and centrifuge) methods for cleaning water ("elaborate on a method/means"):

> *We can filter it with sand or some other media. You could boil it and distill and re-condense it. You could build a centrifuge. If you're really going to do this, you need to know how clean is clean and what your objectives are, because then you're going to be able to generate a solution relative to your requirements. Oh, by the way, now you also have a way to test it and validate it.*

FIGURE 2 Sample data set and patterns that emerged from the data



Across both problems, this participant "focused on the setting/scenario" (solar oven in the American Southwest; clean water for a fishbowl) and "elaborated on a method/means" (three detailed ways to heat an area and to clean water) as seen in Figure 2. These common patterns of problem exploration appear at the center of the Venn Diagram representing his exploration patterns in Figure 2 to indicate they were in both problems. To the left, "detail the required functions" and "apply operational requirements" indicate patterns emerging only in the Solar Oven discovered problem, while "break down the primary need" is positioned on the right to indicate that the pattern was observed only in the Clean Water discovered problem.

4.4 | Study validity

To mitigate threats to validity and reliability, we designed the study to triangulate evidence by including multiple data sources for each participant while they worked on multiple problems in addition to employing more than one coder for data analysis (Johnson, 1997). The first and second authors conducted and recorded sessions independently with individual participants, observing them as they sketched, thought aloud, and responded to questions about their solutions and problem explorations (method triangulation). In the process of coding, low inference descriptors such as verbatim quotes were used to interpret meaning; but because these authors participated separately in both data collection sessions and data coding, descriptive and interpretive validity were strengthened while mitigating research bias. The first and second authors also independently evaluated all of the data collected for the Disaster Relief and Clean Water problems to identify emergent as well as previously discovered patterns. This approach enhanced descriptive and interpretive validity because multiple researchers observed data collection procedures and assigned meaning to the data. The trustworthiness of this analysis plan is revealed through the Cohen's Kappa values shown in Table 3. The study's validity was further strengthened by method triangulation because more than one method provided details about problem exploration.

5 | FINDINGS

The 35 participants generated 376 solutions and corresponding discovered problem statements, with an average of 5.5 ($SD = 3$) and a range of 1–12 concepts (and discovered problems) per presented problem. Thirty-four participants completed two problem exploration tasks while one chose to complete only one. Below, we present evidence of reframing the presented problems, the patterns identified during their problem exploration, and how some of those patterns align with existing non-research-based strategies for problem exploration used in engineering scenarios. It was clear that engineers used strategies to explore problems, as evidenced by the patterns of problem exploration that emerged from the data. Henceforth, we use the term *Problem Exploration Perspectives* to describe research-based strategies of problem exploration that may be useful to novice and experienced engineers alike as they explore design problems.

5.1 | Changes from presented to discovered problems

First, we examined all discovered problem descriptions to determine whether the participants actively reframed the presented problems. Participants identified significant changes they made to the presented problems, and these related to their solutions. For example, in the Disaster Relief design problem, participants documented that they shifted priorities to focus on immediate needs and communication:

> **Participant 15:** *Victims of disaster often are left homeless and without electricity. While the priority of rescue workers is rescue, the supply of food, water, and shelters, the victims are left without electricity for [a] long time. Task is to design deployable, easy to set-up and easy to use devices that can compensate for loss of electricity for the victims.*
> **Participant 27:** *Think about what is immediately necessary to sustain a group of people who have had a disaster. Food, medical, assuming for a while no one can really deploy large "help."*
> **Participant 45:** *Allow people affected by natural disasters to communicate with friends/family to let them know they're okay.*

Participant 15 acknowledged that the presented problem prioritized rescue, food, water, and shelter; however, he decided to address the lack of electricity instead. Participant 27 focused on providing victims with food and medical attention immediately after the occurrence of a natural disaster, while Participant 45 emphasized connecting victims with family and friends to discuss the current state of their safety. These three discovered problems are different from one another, as participants stated different needs and made differing assumptions to frame the design problem. The designers differed in the level of detail in their discovered problem statements, though most wrote concise descriptions of discovered problems while relying on the context provided by the presented problem.

Differing interpretations and intentional shifts of problem focus were evident within all four problem contexts. For example, consider the reframing in the Playground design problem:

> **Participant 14:** *You have to come up with the layout for a park situated in a corner lot with the detailed type and location of each of the equipment that would be placed in the park.*
> **Participant 41:** *There is a need for a way to create a nature park of only local plant species found in my neighborhood.*
> **Participant 47:** *A resident has donated some land to build a play area that will be undercover, which means you don't have to worry about outdoor conditions. Design indoor play equipment for both children and adults.*

Participant 14 directed her effort toward exploring possible playground equipment and layouts for the corner lot, and she identified the place as "a park." The phrase "locally sourced materials" was interpreted by Participant 41 as utilizing native plants indigenous to the area. This perspective aligned with her idea to place the playground in a "wilderness" park environment. In the last example, Participant 47 avoided the constraint of utilizing materials that can withstand outdoor conditions by reframing the problem to focus on an indoor playground.

5.2 | Research Question 1: What patterns of problem exploration emerge as mechanical engineers develop solutions to design problems?

Twenty-seven distinct patterns of problem exploration were evident across the data. Their definitions and appropriate examples are shown in Table 4. We previously introduced 24 Cohen's Kappa values in Table 3 to describe the patterns utilized within the context of the Clean Water design problem; the difference in the number of patterns can be attributed to the lack of use of three strategies in the context of this problem. Of the 27 strategies, 20 align with those observed in the previous study of patterns of problem exploration (Studer et al., 2018). Seven new patterns were added to the set in this study, including four in the top 10 patterns regarding frequency of use: *Break Down the Primary Need*, *Elaborate on a Method/Means*, *Focus the Setting/Scenario*, and *Detail the Operational Requirements*. The other three new strategies, *Break Down the Primary Stakeholder Group*, *Describe the Required Maintenance Needs*, and *Expand the Scope*, were observed less frequently. The frequency of pattern use across all 376 solutions and discovered problem statements ranged from 5 to 129, with a median of 19. Patterns were counted only once per solution/discovered problem (ignoring repeated strategies within each). Examples from the observed data are summarized to describe the ways in which the patterns of problem exploration appeared across design problems.

The patterns observed infrequently were found in all four problems; however, the problem context may have influenced the selection of some exploration strategies. For example, *Focus the Scenario/Setting* was more prevalent in the Disaster Relief discovered problems than in the Playground or Solar Oven discovered problems. Perhaps, participants perceived disasters as more general or complex, occurring with multiple causes. To make the Disaster Relief design problem more manageable, participants may have chosen to focus on particular situations or settings as a strategy.

5.3 | Research Question 2: To what extent do mechanical engineers employ similar patterns of problem exploration across problem contexts?

5.3.1 | Problem Exploration Strategy patterns by problem

The most frequently observed Problem Exploration Perspectives across the four problems as shown in Figure 3 were *Break Down the Primary Need* (129 instances), *State the Primary Need* (114 instances), and *Describe Characteristics of Setting* (87 instances). Both *Break Down the Primary Need* and *State the Primary Need* were applied to prioritize problem components. For example, in the Disaster Relief design problem, *Break Down the Primary Need* was often applied to discovered problems when participants separated the primary components of the design problem, such as participants writing separate problem statements to address shelter, food, and rescue needs. *State the Primary Need* described the situation when the discovered problem referred to one primary need. For example, in the Clean Water design problem, the level of water cleanliness was not defined, so some participants formulated problems with the need for filtered water to clean clothes, while others explored purification processes for potable water. *Describe the Setting* revealed interpretations of the setting; for instance, in the Disaster Relief design problem, participants added statements about closed roads, limited resources, and specific environments (suburban cities, developing nations, or indoor locations).

5.3.2 | Problem Exploration Perspective patterns by participants

Data from 32 of the 34 (94%) participants (with two problem sets) revealed that participants predominately employed both common (or cross-problem) and unique (or problem-specific) strategies between their two problem contexts. Strategies were shared across problems, and others were unique to a given problem. Only one participant showed no overlap in their use of strategies across the problems, and one participant used the same Problem Exploration Perspectives in both of their problem contexts.

Figure 4 presents an illustrative example of three Playground—Solar Oven design problem pairs for a practitioner, graduate student, and undergraduate student. Participant 48, a practitioner, focused on the needs of users, materials, and the setting for both problems. For the Playground discovered problem, the participant stated the primary users were children; that their need

TABLE 4 Problem Exploration Perspectives extracted from participant data

#	*f**	Perspective	Definition	Summary of data examples
1	129	Break down the primary need (NEW)	Analyze the primary need of the desired solution and break it into different smaller pieces. Choose one of the subcategories to focus on and detail it in the problem statement. This will help narrow the scope of the problem.	Shelter, food, and rescue as separate problems ([a]P-1, 8, 12, 14[b]. . .); foil reflection, temperature regulation, and direct exposure to the sun are necessary for a solar oven to work (P-8, 34, 41, & 48); weatherproof materials, different types of play equipment, and working within dimensional boundaries are important for the playground problem (P-14, 20, & 33); water needs to be collected, cleaned, and transported (P-2 & 12).
2	114	State the primary need	Determine the primary need for the desired solution that will solve the limitations of the current state. This will answer the question, “what are you trying to achieve by solving this problem?” Detail the need in the problem statement.	People need individual portions of water to drink (P-1, 12, & 30); the purpose of the playground is to get kids to exercise (P-41); the primary need is to cook food (P-4, 8, 16, 17. . .).
3	87	Describe the setting	Analyze the non-natural environment in which the final solution will be implemented. Describe the conditions of the environment and the limitations that exist in the problem statement. This includes the availability of power and internet and descriptions of the social and political climate or typography. It does not include the weather (rain, snow, hail) or general climate references.	The infrastructure is damaged, and land transportation is not possible (P-7, 8, 9, 12, 17, 32, 35, 36, & 38); there is limited access to electricity (P-42); there is no water supply (P-2); the area is remote (P-7); it will be used indoors (P-34); the setting has lots of trees and plants (P-42).
4	60	Elaborate on a method/means (NEW)	The specific details about the solution are discussed rather than leaving ideas at a conceptual level. How exactly will the device or process function and more importantly, how will it accomplish its overall goal?	Extensively discusses the three processes to clean water (P-10, 15, 28, 30, 34, 35, 39, 44, & 46); kinetic energy is transferred to electrical energy to provide electrical current (P-9); a chemical exothermic reaction offers the warmth necessary to warm victims (P-10); detailed bio-sand filter is described to clean water (P-30).
5	56	Describe the users' need	Determine who the end users of the final solution will be. Define specific criteria that the solution must adhere to that will benefit these users and their experience with the final solution. This includes criteria for ease of use, ergonomics, and safety.	Consider safety of the children who will climb to tall heights (P-20); shelter must be tall enough to feel comfortable (P-29); the solution is easy to use and disassemble (P2, 16, & 37); provide pictorial instructions for victims to operate the device (P-45); the population is tribal; situate the solution according to their values (P-2).
6	48	Focus setting/ scenario (NEW)	Determine a specific situation or place for the operation of the device or solution. Rather than generalizing a solution for use in other situations or scenarios, tailor the solution to a particular use. For example, matches are a universal solution for starting fires, but not when the environment is wet. Instead, another device must be used to start a fire.	The device is to be used during a flood (P-1, 32, 36, 45. . .); the device collects rainwater in the desert (P-7); focus on removing insoluble particles from water (P-16, 39, 40, & 46); the solar oven is to be used in the American Southwest (P-27 & 46).
7	48	Describe material characteristics	Think about the specific material needs of the final solution and describe the necessary characteristics the material must have in the problem statement. The characteristics may include durability and elasticity, among others.	The shelter must be waterproof or resistant (P-8, 33, 42, 45, & 47); need metal rods and a CO_2 cartridge (P-10); the solution is made of metal, rubber, and plastic (P-30).

(Continues)

TABLE 4 (Continued)

#	*f**	Perspective	Definition	Summary of data examples
8	34	Detail the operational requirements (NEW)	What conditions need to exist for the product or process to operate the way it was intended? Is it operated manually, remotely, or with the aid of the external environment? For instance, a grow toy will only grow if it is placed in water or some other liquid. On the other hand, a solar panel will not collect energy unless there is light.	The device needs to operate on its own (P-14); needs to charge for 12 hr (P-17); must be operated remotely (P-7); the water pump requires electricity (P-30); the solar oven should function without the sun's light (P-34).
9	28	Determine the primary user	Determine the primary user of the device or solution. List or describe who they are in relation to the situation or scenario.	For families (P-1 & 8); for children (P-1, 41, 42, & 48); for astronauts (P-41); for sailors (P-41); for individuals (P-12).
10	28	Utilize existing solutions	Instead of exploring ways to design a device, the designer decides to use an existing device to solve a problem or shift the problem definition to a problem that does not require a device.	Uses tents and FEMA trailers as temporary shelters (P-8); utilize a bio-sand filter (P-34); use a household appliance to cook food (P-8, & 34); use a pre-designed play set for the park (P-32); use glow sticks for light (P-17).
11	24	Describe the desired dimensions	Analyze the setting and the use cases of the desired solution. Determine the size of objects in the setting or of the device or solution to be designed. The designer may consider multiple factors when making decisions about actual or preferred size.	The height of the bridge must be no higher than 2 ft. (P-42); determine the space necessary to transport food and supplies to victims (P-14); set the size of the corner lot and the play equipment with it (P-33); detailed dimensions of the slide (P-30); there is a need for a large surface area (P-29); a 6″ by 6″ surface area (P-20).
12	22	Integrate mobility	Analyze the specific scenario in which the desired solution might be used and integrate the need for mobility (can be moved from place to place).	The trailer shelter is on wheels to move into and out of the disaster area (P-8 & 9); the clean water device is portable so people can move outside a zone that has a source of water (P-42); the solar oven is portable so that it can be placed at a location with the most direct sunlight (P-4, 31, 34, & 39); the device is lightweight and can be folded to be moved into storage (P-28).
13	20	Determine the required cost	Analyze the economic status of the individuals, local communities, nations, and appropriate other entities that will use the final solution. Estimate final costs of the solution.	The device should be inexpensive (P-4, 29, & 48); optimize cost and surface area (P-29); the shelter should be low cost and reusable (P-45); the process of cleaning water should be cost efficient (P-12).
14	19	Break down the primary stakeholder group (NEW)	Brainstorm the different groups within the initial stakeholder group you identified. Select a specific group as the new primary stakeholder to encompass more individuals and detail it in the problem statement.	A playground for adults (P-31 & 47); playground for children and adults (P-31 & 47); playground for pets (P-47); transport water to a large town or undeveloped countries (P-12).
15	16	Detail the required functions	Determine and describe in detail the function(s) of the device or system based on the goal, purpose, or needs of the situation.	Provide wireless electricity (P-37); the functions of the device are to carry food, communicate with rescue device, and navigate to a safe place (P-14); primary purpose is to check glucose (P-17); provide shelter and double as a rescue signal (P-12); to deliver water to those who need it (P-2).
16	15	Describe environmental conditions	Describe the environment in which the final solution will be implemented. Describe the conditions of the natural environment (weather, topography, climate, and biomes).	It rains a lot (P-2); victims live on top of a mountain (P-2); water needs to be transported to the desert (P-7); brutal climate (P-12); no rain because it is the dry season (P-34).

(Continues)

TABLE 4 (Continued)

#	*f**	Perspective	Definition	Summary of data examples
17	15	Focus on eco-friendly solutions	Evaluate the environment in which the final solution will be implemented. Detail-specific criteria that the solution must adhere to that will benefit the environment— the ecosystem and the resources, among others. Think about issues such as material waste, climate change, use of natural resources, and so forth.	Incorporate recycled materials (P-4, 30, 42, & 45); reduce environmental impact (P-34); use materials that exist on land (P-32); use donated materials (P-47).
18	14	Describe secondary functions	Describes additional functions beyond the primary function of the device.	Besides providing power, the device should also provide Wi-Fi (P-17); filtering water is the priority, but the device should also transport the water to those in need (P-7, 10, 28 & 34); the primary function is cleaning water, but it needs to be portable as well (P-10); the power supply is primarily for victim relief; however, it also acts as a distress signal (P-35).
19	13	Prioritize use cases	The designer decides the priority of use for the device.	The generator is for charging phones (P-36); power source is for light, cell phone charging, and stress signal (P-35); the solar panel will provide electricity to a stove (P-41 & 43); the solar oven is for cooking pasta (P-2); the solar oven is for cooking eggs (P-2); the solar oven is for popping corn (P-2).
20	12	Modify existing solutions	The designer decides not to design a device but instead alters an existing device to satisfy the needs of the current situation.	Alter a straw filter (P-2 & 12); modify a trailer to suit the needs of disaster victims (P-8, 9); similar to a modern stove or conventional oven (P-34); modify an inflatable castle for shelter (P-9); modify a military tent (P-9); modify a greenhouse so people can live in it (P-29).
21	12	Incorporate more scenarios	List additional settings and situations where the solution could solve a problem.	Water for drinking or for washing (P-35); not just for a disaster, but wherever there is a blackout (P-37); the power device can be used in areas that are not affected by weather (P-1 & 47); the device can travel on land and water (P-7).
22	8	Describe the required maintenance needs (NEW)	Determine how the desired solution will be maintained or serviced after implementation. What tools/labor are required? The maintenance criteria should be defined to suit the environment and situation of the desired solution.	Repaint on a yearly basis (P-4); the lawn needs to be mowed at the park (P-48); the playground needs to be painted on a biennial schedule (P-4).
23	8	Describe the desired appearance attributes	Describe the visual qualities needed to support the primary functions to enhance the users' experience with the outcome. This could be functional or aesthetic.	Spherical space under the lid to focus the light on the food (P-20); make it in the shape of a box (P-8); the playground should have eye appeal and the playset should coordinate with the rubber base (P-4); use dark material or paint to absorb the sun's energy (P-20).
24	7	Describe an existing solution to use as conceptual inspiration	An existing product serves as a metaphor, analogy, or simile for the solution.	Helicopter “rains” on dry land; instead of dropping fire retardant, the helicopter releases water (P-2); use the analogy of your car getting hot in the summer (P-27); use the concept of focusing light with a lens to burn paper (P-27); it is the same principle as frying an egg on your car (P-2).

(Continues)

TABLE 4 (Continued)

#	*f**	Perspective	Definition	Summary of data examples
25	5	Expand the primary stakeholder group	Make a list of larger groups that involve the primary stakeholder group. Select one of these groups to encompass more individuals than the initial primary stakeholder group you identified.	The playground is for people and pets of all ages, not just for kids (P-47); the playground is for people of all ages (P-42); the park is for teens and adults (P-42); the rescue team reaches out to a manufacturer (P-17); the discovered problem includes local government representation (P-17).
26	5	Expand the scope (NEW)	Analyze the primary outcome of the desired solution and add scope to the goal (while still being manageable) to maximize the benefits of the final solution.	It is more than a playground; it doubles as a concert-in-the-park venue (P-42); the solution includes empowering victims to create a community among victims, so they may work more efficiently in their rescue efforts (P-27); think about how to prevent the growth of bacteria in potable water supplies (P-44).
27	5	Add potential limitations	After analyzing aspects of the problem, determine possible limitations to a solution search.	Only two materials can be used (P-41); consider the constraints on cleaning water in a poor resource area (P-45); the roads are damaged due to the natural disaster; therefore, road transport is not an option (P-7).

[a]P indicates participant.
[b]. . . indicates too many participant examples to list in the space allotted.
[*]f = frequency.

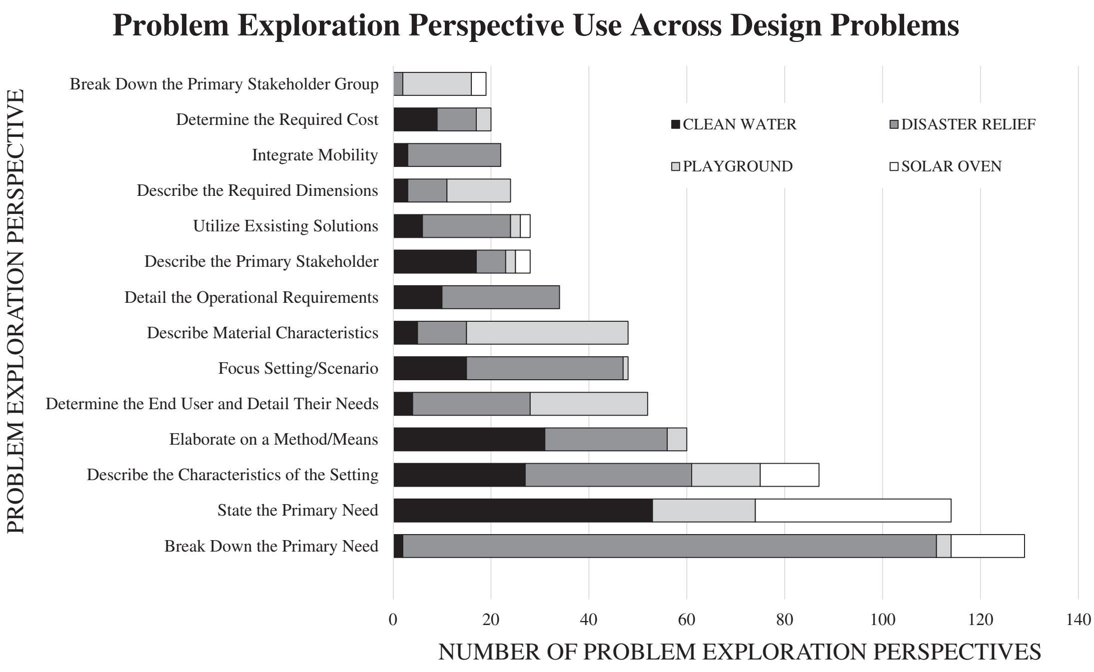


FIGURE 3 The most commonly observed Problem Exploration Perspectives across four design problems

was to cool off on a hot day; and that running, swimming, and playing basketball would prevent or reduce the risk of becoming obese. In the Solar Oven discovered problem, the user was defined as anyone operating the oven, and their need was for simplicity. In both problems, the participant described the materials as durable. All the discovered problems specified developing nations as settings for the solar oven; however, setting descriptions for the Playground discovered problem included open fields, native arboretums, and lots with trees. In the Solar Oven context, the participant chose to work with one setting (developing countries), while broadly exploring the setting in the Playground design problem. Problem explorations

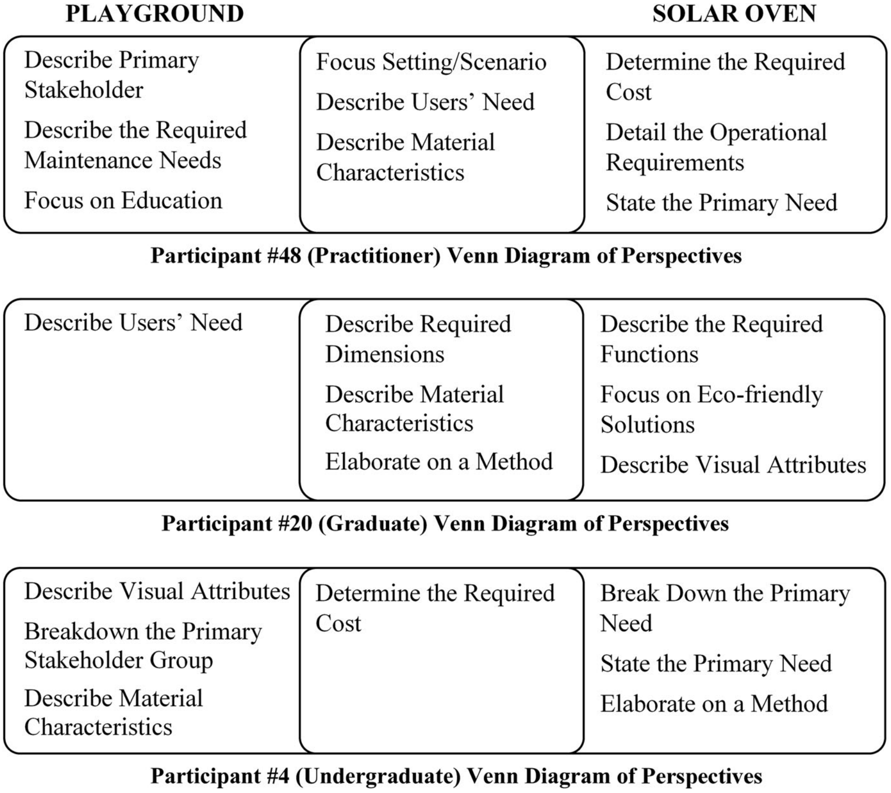


FIGURE 4 Unique and common perspectives across problem pairs

specific to the Playground design problem included a focus on different stakeholders, art and music education, and regular and intermittent maintenance. Cost, function, and breaking down the primary need were evident in the Solar Oven discovered problem.

Participant 48 considered a spectrum of stakeholders spanning a small group of users (young children or older kids) to the community at large. One particular exploration of the problem led to a focus on art and music in the form of viewing, listening to, and interacting with the available musical playground equipment. According to Participant 48, all of his ideas required preservation. From cutting the grass every week to resurfacing the running track, a plan was necessary to attend to the dynamic nature of the materials. In the Clean Water design problem, Participant 48 indicated the device must be inexpensive, simple to use, and function daily. The primary need was to create a device that anyone could use with little or no instruction.

Participant 20 also shared a set of common strategies across the Playground—Solar Oven design problem pair; however, the set of strategies was different from those used by Participant 48. Participant 20, a graduate student, emphasized dimensions and materials, and elaborated on a method. Dimensions were explicit for a play cube, the base of the solar oven, the volume of a water container, and the height of a bridge that connected two sections of playground equipment. The materials were also apparent as the participant stated wood, bolts, and a cargo net were the building blocks of the playground, while non-BPA plastic, copper plates, brick ovens, and a steel or aluminum reflective dish were necessary for building a solar oven. In both discovered problem sets, the dimensions and materials contributed to describing or elaborating on how the participant was going to solve the design problem.

The difference in the use of strategies was evident in the problem pair when Participant 20 focused on the function, eco-friendly materials (non-BPA), and visual attributes of the solar oven, while the focus was on the user and stating the primary need for the playground. Participant 20 focused on the function of the solar oven by selecting materials and creating shapes (visual appearance) conducive to a functional oven. Safety (user's need) was apparent when rails were proposed to be placed at the top of the play equipment to prevent a fall.

The last example comes from Participant 4. The only common feature of the Playground—Solar Oven problem pair was attention to cost. The undergraduate in both cases prioritized the low cost of the designs, but from there the strategies diverged. Observed in the playground data were a visual appeal, materials, and the primary stakeholder. In both Playground discovered problems, Participant 4 noted that the playground design had to be appealing to the community although children were the primary stakeholder. One design centered on the use of wood, while the other focused on plastic because the materials were not expensive. The primary need of the Solar Oven problem fluctuated between cooking specific foods such as hot dogs to the preparation of a variety of foods. Moreover, each of the three Solar Oven discovered problems included detailed explanations about how to power the solar oven with the sun.

These three examples of the Playground—Solar Oven design problem pair illustrate how three participants explored two problems with common and unique strategies. The problem pairs were explored differently by each participant. Even the use of strategies associated with the Playground, Solar Oven, and Playground—Solar Oven design problems were distinct across the problem pairs. These patterns of strategy use suggest there may be individual preferences for specific strategies such that some are viewed as more primary and utilized more often, and others are more specific to problem context. Further research on problem exploration is needed to identify individual preferences across problems.

6 | DISCUSSION

Comparing Problem Exploration Perspectives across two problem contexts, we found that most participants employed strategies both across problems and in a single problem (applied uniquely within one design problem). Our findings provide clear empirical evidence that mechanical engineers explored design problems in multiple ways using specific exploration strategies. The identified strategies were not observable from solution concepts alone; articulation of their perspectives on the problems contributed to the recognition of strategy use. The 27 Problem Exploration Perspectives observed in this study align with those found in a very different sample of problem exploration: an online design challenge where multiple individuals posted independent designs and discovered problems over the challenge period (weeks). The observed high overlap (74%) between exploration strategies in these two studies suggests they are robust and useful across tasks, and are observed in use across designers and many different design problems.

A few of the Problem Exploration Perspectives identified here share similarities with two more general strategies previously suggested: Selective Focusing (Shull et al., 1970) and Problem-Definition Process (Spradlin, 2012). Demonstrations of Selective Focusing occurred when engineers emphasized problem components and manipulated environments, scenarios, and limitations. For example, designers shaped malleable features and chose to set weather, setting, and other elements not fixed in the presented problem: (a) corner lots were "wooded" in the Playground problem (*Focus on the Setting*), (b) water was "60 miles away" in the Clean Water problem (*Focus on Scenario*), (c) "power" was prioritized in the Disaster Relief problem (*Break Down the Primary Need*), and (d) a solar-powered oven was deemed more reasonable than a solar oven (*State the Primary Need*). Other Problem Exploration Perspectives identified in this study helped to narrow the problem scope, including *Describe the Primary Stakeholder*, *Focus on the Setting/Scenario*, *Add Potential Limitations*, and *Focus on Eco-Friendly Solutions*. These strategies, whether applied alone or in combination, helped designers to bound potential constraints and specify a discovered problem.

Another proposed strategy, referred to as "contextualizing," associated with Spradlin's Problem-Definition Process (2012), also emerged in this study. Participants contextualized design problems by choosing specific disasters, creating solar ovens for particular regions, designing playgrounds for city kids, and finding a supply of clean water in a desert. One exception was the Clean Water design problem; perhaps they imagined general approaches to work in any situation because water is needed in every context. Overall, the strategies, *Describe the Setting*, *Describe the Primary Stakeholder*, *Describe the Environmental Conditions*, and *Shift the Focus to Cultural Issues*, were more often used when participants chose to contextualize the problem.

The discovered design problems observed in this study suggest the need for a more complex view of design problem definition. While design problems are considered ill-structured when no defined operators lead to solutions (Simon, 1977), in practice they may contain both well-structured and ill-structured components. For example, in the Disaster Relief design problem, ambiguous elements include (a) who will deploy the device (relief worker, victims, etc.); (b) who will use the device; (c) the purpose of the device (providing food, light, warmth, shelter, etc.); (d) the time frame; (e) victim relocation; and (f) what defines the disaster. Whether specific operators are applicable may depend upon how the designer chooses to frame the problem and whether existing solutions are evident. A qualitative study of workplace engineering problems noted they are ill-structured and complex, with conflicting goals, multiple solution methods, nonengineering constraints, and variations in problem representations (Jonassen, Strobel, & Lee, 2006).

Engineering designers in our study showed a great deal of variation in their problem perspective, that is, in how they framed discovered problems. Some opted to create a more general device for any disaster, while others focused on narrowing the problem. For example, many participants focused on shelter, food delivery, lighting, warmth, sources of power, and forms of communication useful in any disaster relief effort; however, other approaches were context-specific, and the reframed problems addressed water-related disasters including the transport of victims to dry land using location sensors and vehicles. Some discovered problems addressed altogether different problems from those presented. In some cases, the engineers did not design devices at all and used pre-made power and communication channels. With the right perspective, they could dispatch electricity to the site efficiently and obviate the need for a device to help sustain victims for days or even weeks on end. Future research may determine how the use of strategies to narrow or broaden the scope of presented problems impacts solution qualities or results in a similar broadening or narrowing in the range of solutions generated.

The engineers explored the presented problems to arrive at differing perspectives. For some, the presented problem appeared well structured, and they designed devices to help victims; however, others saw the same problem as unstructured or malleable (Goel & Pirolli, 1992) and redefined the underlying problem(s), enabling a broader range of solutions. Because a variety of pathways were observed between presented problems and solutions, a more nuanced theory of problem formulation may be necessary to account for designers' choices. Problems with more structured (clear path toward a solution) components may suggest a convergent exploration process, while unstructured (ambiguous path toward a solution) problem elements may prompt more divergent exploration. While the current study provides only limited numbers of different solutions generated due to the short design session, further research may examine connections between alternative paths through problem exploration processes and the solution generation.

Importantly, these findings illustrate that different mechanical engineering designers exploring the same problems utilized *different* exploration strategies for each solution and discovered problem. The differences in strategy use may be attributed to individuals' prior experiences (Holyoak, 1984; Mumford et al., 1994; Simon, 1973) or values (Lloyd & Scott, 1994; Schön, 1984). Individuals draw from unique experiences and gravitate toward familiar problem features (Mumford et al., 1994) not shared by others. For example, in the Disaster Relief problem, many designers reframed the problem to focus on restoring or providing power, perhaps drawing from their experiences of power outages or televised disasters. Previous research supports this claim that individuals reframe problems to align with their previous experiences (Dorst & Cross, 2001; Schön, 1988; Stumpf & McDonnell, 1999).

The findings from this study are also important because they are the first empirically derived Problem Exploration Perspectives documented during the design process. The exploration strategies may be useful in considering new design problems, expanding perspectives on problems and encouraging the formation of new perspectives broadening solution possibilities and leading to more innovative ideas. The prior study by Studer et al. (2018) identified a relationship between evidence of problem exploration and successful outcomes in design challenges. Further research is needed to document this link between Problem Exploration Perspectives and the production of more and varied solutions in the design process. Additional research may combine these approaches to determine the relationship between problem features and strategy use. Identifying how exploration patterns may be aptly applied based on problem characteristics would be helpful in designing instructional materials for engineering students.

6.1 | Limitations

Several limitations should guide conclusions from this study. The research method captured engineers' design processes while working alone in a time-limited, single session with short, general presented problems. This method may not represent design settings where engineers work with others in teams, engage in much more extended design periods, and take advantage of incubation and rest periods while they shift to other tasks or return another day. The study may also underestimate changes during problem exploration because it did not employ information gathering, stakeholder feedback, or other information such as team input. In real-world practice, engineers are free to consult other people and resources, develop investigations, and collect data before making decisions affecting the problem-solution space. The information-gathering phase of design (Kruger & Cross, 2006) and human-centered design concerns (Norman & Draper, 1986) were not included in this study; instead, designers had to rely solely on their own interpretations of the brief.

Our study method may be a better match to traditional engineering education settings where "paper" problems are presented to illustrate only some important qualities of real-world design problems (Jonassen et al., 2006). Because our goal was to observe problem exploration evident in engineers' thinking during design, the short design problems (similar to those in other published studies) and short session protocols provided adequate design engagement. To enhance this method, we included multiple design problems and asked each designer to address two different ones, allowing comparisons across problems.

The study employed a convenience sample (Teddlie & Yu, 2007) from two mid-western locations, and purposive recruitment included a small range of engineering specializations and levels of experience. Participant gender demographics do not represent an equal balance across gender. We did not document the ethnic or socioeconomic composition of the sample; so, it is not possible to determine how well the sample represents larger populations. This descriptive study did not compare groups to draw inferences from the sample; instead, our intention was to observe and document the occurrence of problem exploration during active design sessions.

6.2 | Implications of Problem Exploration Perspectives for engineering education

Problem Exploration Perspectives have the potential to aid engineers in changing problem perspectives through reframing presented design problems. Problem Exploration Perspectives could provide engineers at all levels—from undergraduate and graduate education through professional practice—with prompts to facilitate changes in perspective. Existing design tools assisting idea generation have been utilized across a broad spectrum of expertise (e. g., Al'tshuller, 1999; Allen, 1962; Daly et al., 2012; Eberle, 1995; Hernandez, Schmidt, & Okudan, 2013). To illustrate how to use these strategies when exploring new design problems, we provide an extended example demonstrating how Problem Exploration Perspectives may shift or expand problem perspectives and broaden solution spaces.

The Space Debris design problem presented in Figure 5 describes how debris orbiting the Earth poses a threat to active satellites and space vehicles in the Low-Earth region (Space Debris Problem, 2017). This design problem is ill-structured, so problem exploration is necessary. The application of Problem Exploration Perspectives may diversify problem perspectives during design and lead to more divergence in solutions generated. In the following example, three specific Problem Exploration Perspectives are applied to the presented design problem to create three different discovered problems, illustrating how different strategies create differences in such problems.

In the example, the strategy, *Describe the Required Dimensions*, is first used to spur problem exploration, and a first discovered problem prioritizes space debris smaller than 2 in. Because the U. S. Department of Defense is currently unable to track objects that small, this "invisible" debris poses a threat to orbiting objects like the International Space Station (ISS). Targeting the problem of identifying "invisible" debris shifts the problem focus to tracking space debris that can be detected. The newly imposed problem frame could eventually lead to different solution outcomes better suited to shielding the ISS rather than the protective cover currently safeguarding it.

Space Debris Presented Problem

Space debris—the trash that orbits the earth—is a hazard to the International Space Station (ISS), active satellites, vehicles, and any object traveling from the earth's surface to or through the Low-Earth orbit region (within 1200 miles of the earth's surface). The debris left behind from rockets lifting objects to the Low-Earth orbit, inactive satellites, and collisions among satellites poses a threat to active space objects. At speeds of thousands of miles per hour, debris the size of marbles can have more energy than a bullet released from a machine gun.

The Department of Defense's Space Surveillance Network can track space debris larger than two inches (currently over 21,000 objects). The International Space Station (ISS) has debris shields to protect itself from smaller projectiles; however, recently the ISS was struck by a millimeter-sized piece of debris that left a 1½ inch deep pit in one of its windows. How can we fix the problem of space debris?

Space Debris Discovered Problem 1
Detail Required Dimensions

Space debris of less than two inches in each dimension poses a threat to active objects traveling within 1200 miles of the earth's surface because it is not visible with currently available technology. How can we track small debris?

Space Debris Discovered Problem 2
Use Existing Solutions as Conceptual Inspiration

On earth's surface there are ways to legally and socially deal with pollution. There are rules and regulations for those who violate laws. How can we apply what we know about pollution from other situations to resolve the current space debris issue?

Space Debris Discovered Problem 3
Detail Operational Requirements

Develop a way to safely remove space debris from the Low-Earth orbit region. The solution should not disrupt the path of active satellites or space vehicles orbiting in the region.

FIGURE 5 Extended example of three discovered problems from the presented Space Debris problem

Solution 1

Satellite that monitors the path of small (< 2 in.) space debris.

Solution 2

Create a new international group (U.S., Australia, Europe, & Asia) to create a space debris compact.

Solution 3

Electrically charge the debris. Guide the debris with the electric field generated by the parallel plate capacitor.

FIGURE 6 Solutions that correspond to the Space Debris discovered problem statements

Use Existing Solutions as Conceptual Inspiration was used strategically to create a second discovered problem. In this strategy, the designer thought about similar debris problems occurring on earth, such as litter and pollution. Drawing from government organizations setting standards (such as the Environmental Protection Agency setting pollution standards), this discovered Space Debris problem focuses on prevention by creating policies to govern the future generation of space debris.

Finally, the third discovered problem was guided by the strategy, *Detail the Operational Requirements* under which the device functions. The presented problem states that the device must not influence the path of other active satellites and space vehicles. One interpretation is that the device cannot be functional near active space objects; therefore, an operational requirement—that the device must be switched off when near active space vehicles and switched back on after they pass—is added to define a discovered problem.

These three different problem perspectives yield different approaches in solution generation. Figure 6 illustrates three solutions corresponding to each discovered problem. The first solution is a satellite that tracks small space debris. The satellite orbits in the Low-Earth region to be near debris for radar (or some other tracking mechanism) detection. The second solution focuses on the prevention of further space debris by creating an international venue for coordinating future space vehicle launches and disposals. The last solution targets the removal of small space debris by charging it with electrons produced by a cathode ray tube (electron gun). Once charged, the objects pass through an electrical field, altering the debris' trajectory. Figure 6 depicts the debris burning up in the atmosphere and charged particles deflecting toward the earth's magnetic field, spiraling toward the poles to join the aurora borealis or aurora australis.

This extended example illustrates how Problem Exploration Perspectives can serve to change a designer's understanding of the problem. These strategies provide a focus for the design problem, such as identifying the small space debris as the problem to solve. The second strategy applied provides an analogy connecting removing space debris to handling trash on earth. The third strategy focuses on the operational requirements of the device, suggesting varying the operational characteristics to allow intermittent use. These three discovered problems and solutions illustrate a few of the many possible paths in problem–solution exploration; however, by using these Problem Exploration Perspectives, designers may benefit from new perspectives and solutions. Providing practice with exploring design problems may also support the recognition that presented problems may not provide an identification of the underlying problem(s). In particular, novice designers often view a presented problem as fixed (Purcell & Gero, 1996), so encouraging this realization through training with Problem Exploration Perspectives may support their development as engineers able to investigate and find problems leading to interesting solutions. While problem exploration has long been viewed as an essential component of the design process, these findings provide evidence of how this process occurs in engineering designers.

7 | CONCLUSION

Design research has pointed to the importance of problem exploration in the early stages of design; however, little evidence describes whether and how engineering designers explore problems, and which strategies may guide designers in exploring problems for creative outcomes. This study documented a range of distinct patterns of problem exploration observed through think-aloud protocols of multiple design solutions and discovered problems. The results showed that similar exploration strategies were evident across problems and designers; however, their application produced differing solution outcomes. These identified Problem Exploration Perspectives have the potential to assist other designers in expanding their use of alternative perspectives as they strategically explore the presented problem; as a result, varied perspectives lead to the development of innovative outcomes. In engineering education, learning to intentionally search for alternative views of presented design problems using these strategies may lead students to previously unseen areas of the solution space and more diverse solutions with increased potential for innovation.

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APPENDIX

PREVIOUSLY DETERMINED PATTERNS OF PROBLEM EXPLORATION FROM A STUDY OF ONLINE DESIGN CHALLENGES (STUDER ET AL., 2018)

Category	Problem Exploration Perspective	Problem Exploration Perspective definition
Appearance	Describe the desired visual attributes	Describe the visual qualities needed to support the primary functions in the problem statement in order to enhance the users' interaction with the outcome.
Appearance	Describe the brand values	Describe the aesthetic values desired by the solution or the brand in the problem statement.
Assumptions	Examine assumptions	Identify potential assumptions you need to make for early-phase, preliminary solutions and add to problem statement.
Cost	Determine the required cost	Analyze the economic status of the individuals, local communities, nations, and other appropriate entities that will use the final solution. Define the maximum cost of the final solution.
Current state limitations	Find the root cause	Analyze the limitations or flaws to achieving the task at hand in the current state. Explore what is causing each of the limitations to determine the root cause(s). Specify the root cause as the limitation in the problem statement.
Current state limitations	Add potential limitations	Analyze the limitation(s) to achieving the task at hand in the current state. Detail limitations that may be similar or would benefit from a similar solution and select one or two to add to the problem statement.
Current state limitations	Break down the addressed limitation(s)	Analyze the limitation(s) to achieving the task at hand in the current state. Make a list of all sublimitations within the original one. Select one or two sub-limitations to replace the original limitation in your problem statement.

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Category	Problem Exploration Perspective	Problem Exploration Perspective definition
Environment	Focus on eco-friendly solutions	Evaluate the natural environment in which the final solution will be implemented. Detail specific criteria in the problem statement that the solution must adhere to that will benefit the environment—the ecosystem and the resources, among others. Think about issues such as material waste, climate change, use of natural resources, and so forth.
Environment	Describe the environmental conditions	Analyze the environment in which the final solution will be implemented. Describe the conditions of the environment and the limitations that exist in the problem statement. This includes the climate, topography, labor force, and any existing products that may be used in the same environment.
Environment	Brainstorm ways to eliminate environmental restrictions	Analyze the conditions and limitations of the environment in which the final solution will be implemented and determine if they can be modified, eliminated, or reduced. Change the primary outcome to resolving the environmental constraints in the problem statement.
Functions	Detail the required functions	Brainstorm specific functions that the final solution must have in order to solve the specific issue being addressed. Think about how the final solution will operate ideally and detail each function in the problem statement.
Functions	Describe secondary functions	Analyze the environment and the situation in which the desired solution will be used. Brainstorm specific functions that could be incorporated to benefit the final solution and add them to the problem statement. These will be in addition to the primary function of the final solution.
Functions	Integrate existing products to address secondary functions	Analyze the secondary functions of the desired solution and brainstorm existing products that could be incorporated in the desired solution to provide this additional functionality. Detail these products in the problem statement.
Functions	Describe an existing solution to use as conceptual inspiration	Analyze the primary outcome of the desired solution and brainstorm existing products that have a similar outcome. Use the concept of existing ideas as inspiration for your idea. Determine if the concept of the existing product could be used in a new way to solve the limitation you are addressing and detail it in the problem statement.
Functions	Consider existing solutions	Analyze the primary outcome of the desired solution and determine if an existing solution can be used to solve the problem. If not, describe the functions of similar solutions and identify which functions are applicable to the problem and add them to the problem statement. Address any gaps of the current solutions that still need to be filled and specify these gaps in the problem statement.
Manufacturing/ maintenance	Describe material characteristics	Think about the specific material needs of the final solution and describe the necessary characteristics the material must have in the problem statement. The characteristics may include durability and elasticity, among others.
Manufacturing/ maintenance	Describe the required manufacturing process and its limitations	Analyze the current manufacturing capabilities and detail these capabilities and limitations in the problem statement. These might include processes or materials that must be used or cannot be used.
Manufacturing/ maintenance	Incorporate user customization in manufacturing process	Add criteria that require the ability for the final solution to be customized by the user before manufacturing and detail the features that can be customized in the problem statement.
Manufacturing/ maintenance	Describe the required maintenance needs	Analyze how the desired solution may need to be maintained or serviced after implementation. Describe how or when the desired solution should be maintained and what tools/labor are required in the problem statement. The maintenance criteria should be defined to suit the environment and situation of the desired solution.
Outcome	State the desired outcome	Determine the primary outcome of the desired solution that will solve the limitations of the current state. This will answer the question, “What are you trying to achieve by solving this problem?” Detail the primary outcome in the problem statement.

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Category	Problem Exploration Perspective	Problem Exploration Perspective definition
Outcome	Break down the desired outcome	Analyze the primary outcome of the desired solution and break it into different smaller pieces. Choose one of the subcategories to focus on and detail it in the problem statement. This will help narrow the scope of the problem.
Outcome	Expand the scope	Analyze the primary outcome of the desired solution and add scope to the goal (while still being manageable) to maximize the benefits of the final solution.
Outcome	Shift focus to cultural issues	Analyze the cultural issues present that may have an impact on the limitations of the current state. Describe these issues and modify the primary outcome to fixing these issues to improve the culture in the problem statement. This will shift the focus from individual needs to broader needs.
Outcome	Brainstorm ways to eliminate the root cause	Analyze the current limitations to achieving the task at hand. Determine if the object or situation causing the limitation can be moved in order to eliminate or reduce the limitation and modify the primary outcome to reflect this in the problem statement.
Outcome	Focus on education	Analyze the primary outcome of the desired solution and modify it to teaching individuals/group how to perform a task instead of the primary outcome being to perform a task in the problem statement.
Outcome	Focus on economic growth	Analyze the primary outcome of the desired solution and modify it to include benefiting the economic status of an individual, local community, nation, and other appropriate entities in the problem statement.
Scenario	Integrate mobility	Analyze the specific scenario in which the desired solution might be used and integrate the need for mobility (can be moved place to place) in the problem statement.
Scenario	Prioritize use cases	Analyze potential scenarios in which the desired solution can be used (What are the user(s) doing?). Define the positive/negative characteristics of the situations in which the solution will be implemented and prioritize them based on frequency. Select the top use case and detail it in the problem statement.
Scenario	Incorporate more scenarios	List additional use cases in which the final solution could be used. Detail each use case and add them to the problem statement. This will broaden the ways the final solution could be used.
Scenario	Describe a future scenario	Brainstorm scenarios in which the desired solution could be used in the future. Think about the potential setting, the users, and the products available in the future. Detail one or two scenarios in the problem statement.
Setting	Expand the setting	List additional settings in which the desired solution could be used. Detail each setting and add them to the problem statement. This will broaden the potential areas/spaces in which the final solution can be implemented.
Setting	Define the characteristics of the setting	Analyze potential setting in which the desired solution could be used. Select a specific setting to focus on. Define the positive/negative characteristics of the setting in which the solution will be implemented in the problem statement. If a setting is already specified, provide more detail.
Size	Describe the required size and space attributes	Analyze the situation and space available. Assign a size range or set of dimensions for the setting, solution, or other elements of the problem scenario.
Stakeholder	Substitute the individual primary stakeholder for a group	Make a list of the primary stakeholder's social groups. Select a specific group as the new primary stakeholder to include more individuals and detail the group in the problem statement.
Stakeholder	Substitute the primary stakeholder group for an individual	Make a list of individuals in the primary stakeholder group you identified. Select a specific individual and change the primary stakeholder to this individual in the problem statement.
Stakeholder	Expand the primary stakeholder group	Make a list of larger groups that the primary stakeholder group is a part of. Select one of these groups to encompass more individuals than the initial primary stakeholder group you identified. Change the primary stakeholder to this group in the problem statement.

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Category	Problem Exploration Perspective	Problem Exploration Perspective definition
Stakeholder	Describe the primary stakeholder	Brainstorm all possible stakeholders (both internal and external) of the desired solution. Prioritize and select one stakeholder (individual or group) that will primarily benefit from the solution to add to the problem statement.
Stakeholder	Break down the primary stakeholder group	Brainstorm the different groups within the initial stakeholder group you identified. Select a specific group as the new primary stakeholder to encompass more individuals and detail it in the problem statement.
Stakeholder	Describe secondary stakeholders	Brainstorm possible stakeholders that could benefit indirectly from the desired solution. These stakeholders would be involved in the final solution somehow, but may not be the main benefactors. Describe how these stakeholders will interact with the desired solution or the users of the desired solution in the problem statement.
Stakeholder	List individuals or groups that are associated with the primary stakeholder	Brainstorm the individuals or groups that the initial primary stakeholder may interact with it on a regular basis. Select one of these individuals or groups as the new primary stakeholder in the problem statement.
User	Include multiple ways to interact	Analyze how the user will use the desired solution and add the ability of the user to reconfigure or customize the solution to meet the specific needs of each user and each situation in the problem statement. This includes the ability to add, remove, or change different components.
User	Determine the end user and detail their needs	Determine who the end users of the final solution will be. Define specific criteria that the solution must adhere to that will benefit these users and their experience with the final solution. This includes criteria for ease of use, ergonomics, and safety.